The Sierra Nevada Snowpack: Observed Climate-Snowpack Relationships and Modeling Advances

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Outline

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I. Background

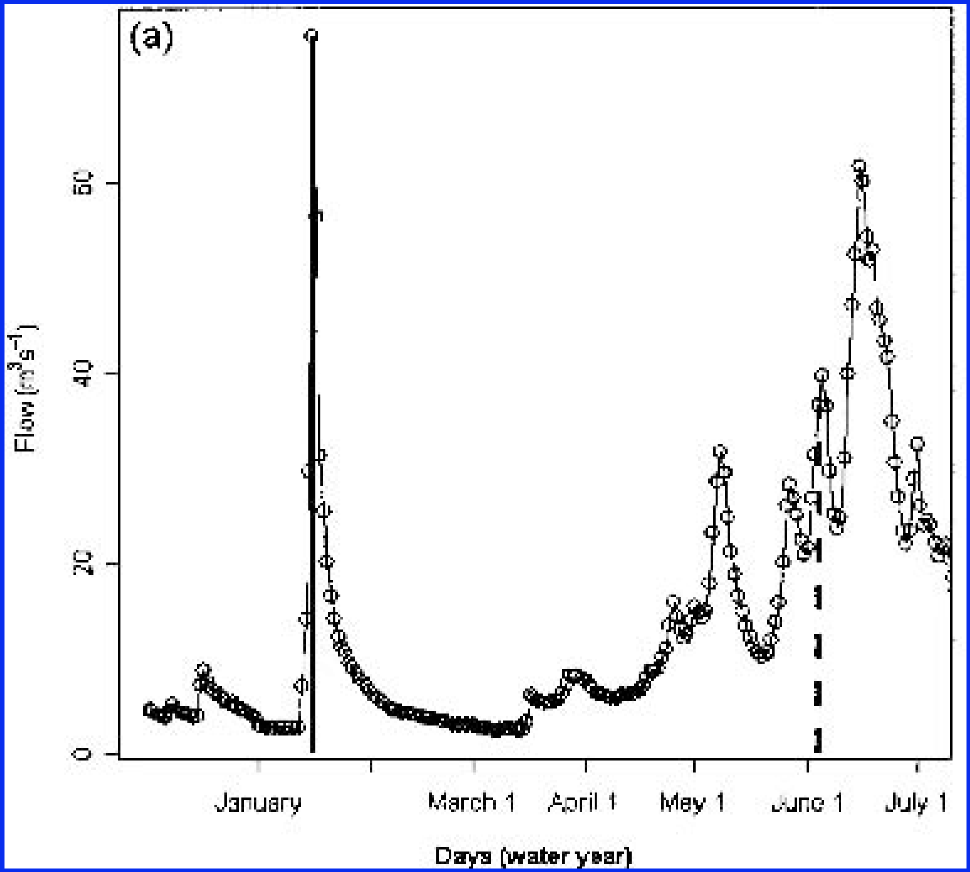
Motivation: Social & Economic

- The Sierra Nevada is a narrow coastal mountain range
  - ~650km in length
  - ~80km in width
- Snowmelt runoff accounts for more than half of the California water supply

Motivation: Past Work is Incomplete

Streamflow Studies

- Streamflow is not a perfect measure of snowmelt, as it can be influenced by erroneous factors:
  - Precipitation
  - Temperature
  - Lithogy
  - Soil composition
  - Vegetation
  - Pre-snowmelt soil moisture
  - Calculation method
- Measurements in changes in streamflow pulse may measure a climatological conversion of a region receiving rainfall instead of snowfall, and not early season snowmelt

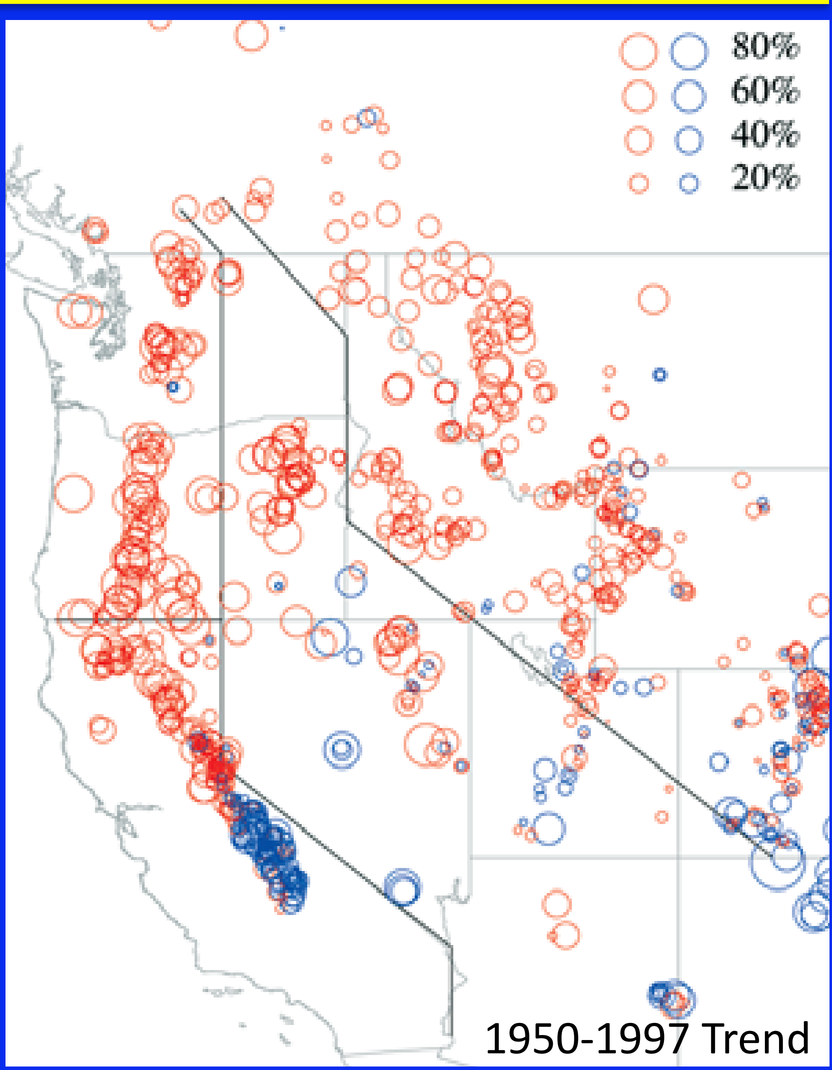


Sources: Aguado et al. 1992, Regonda et al. 2004

Motivation: Past Work is Incomplete

Snow Water Equivalent ("SWE") Studies

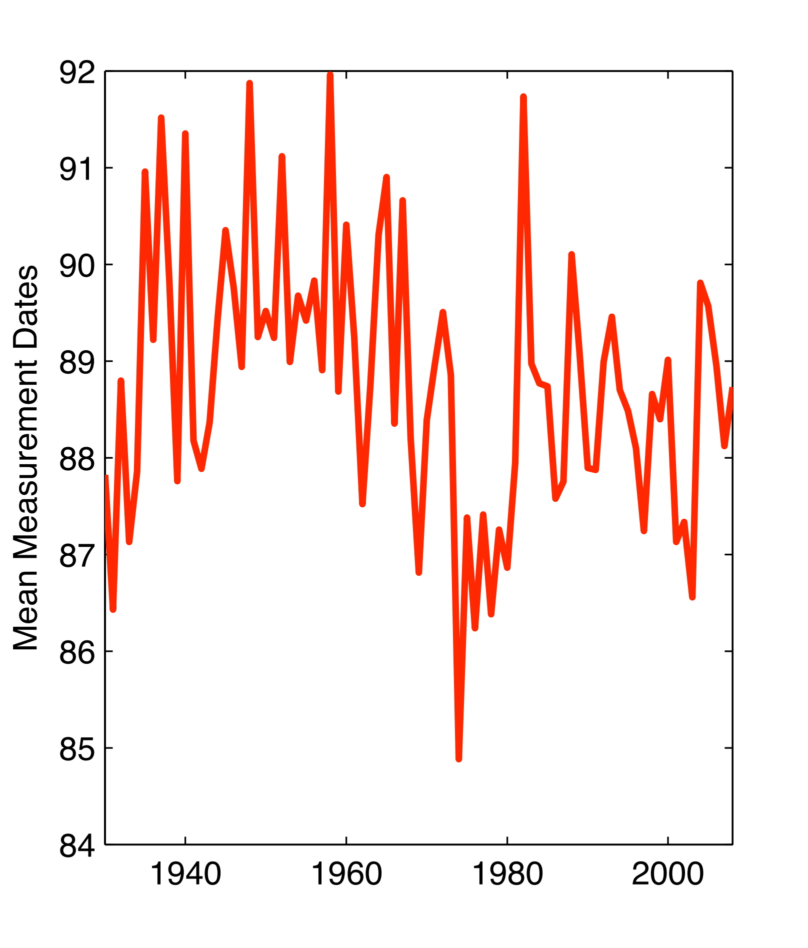
- Only April 1st SWE values were used for trend analysis
  - ✧ Measurements were taken **AROUND** April 1st (within 2 weeks +/-)
    - Papers assume the measurement date would not affect trend analysis
    - Trends in the Sierras are not always statistically significant
  - ✧ This single annual snapshot does not easily transfer into understanding the mechanism for change (precipitation, early season snowmelt, or measurement date error)



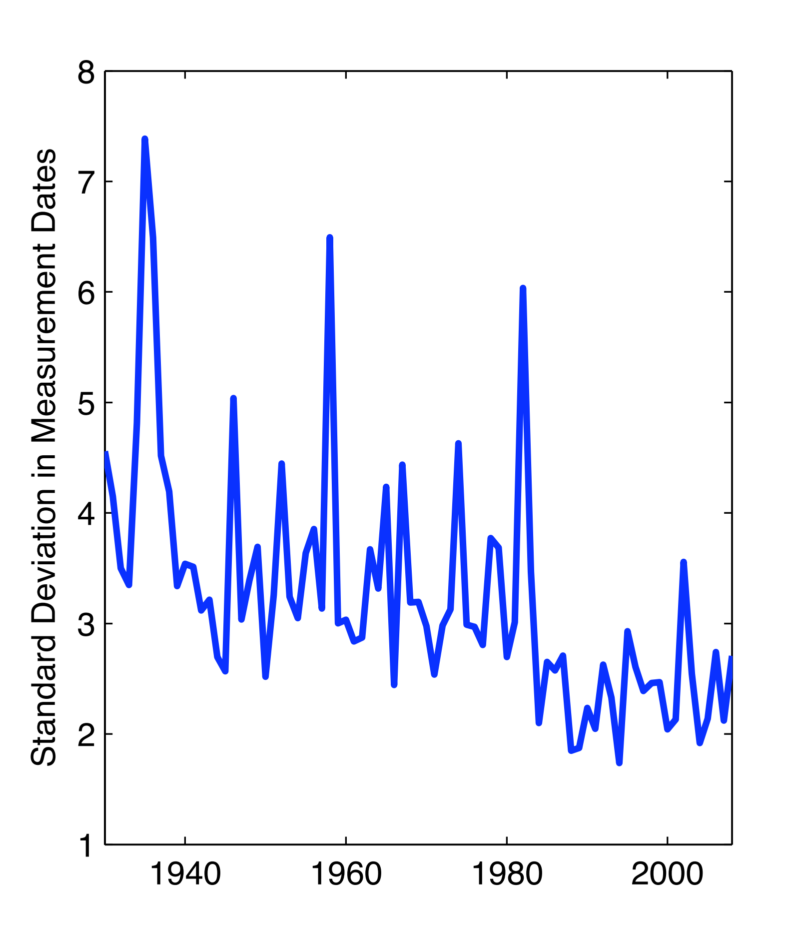
Sources: Mote et al. 2005

Error of Measurement Dates for "April 1st" SWE Values

Mean Measurement Date



Stdev in Measurement Date



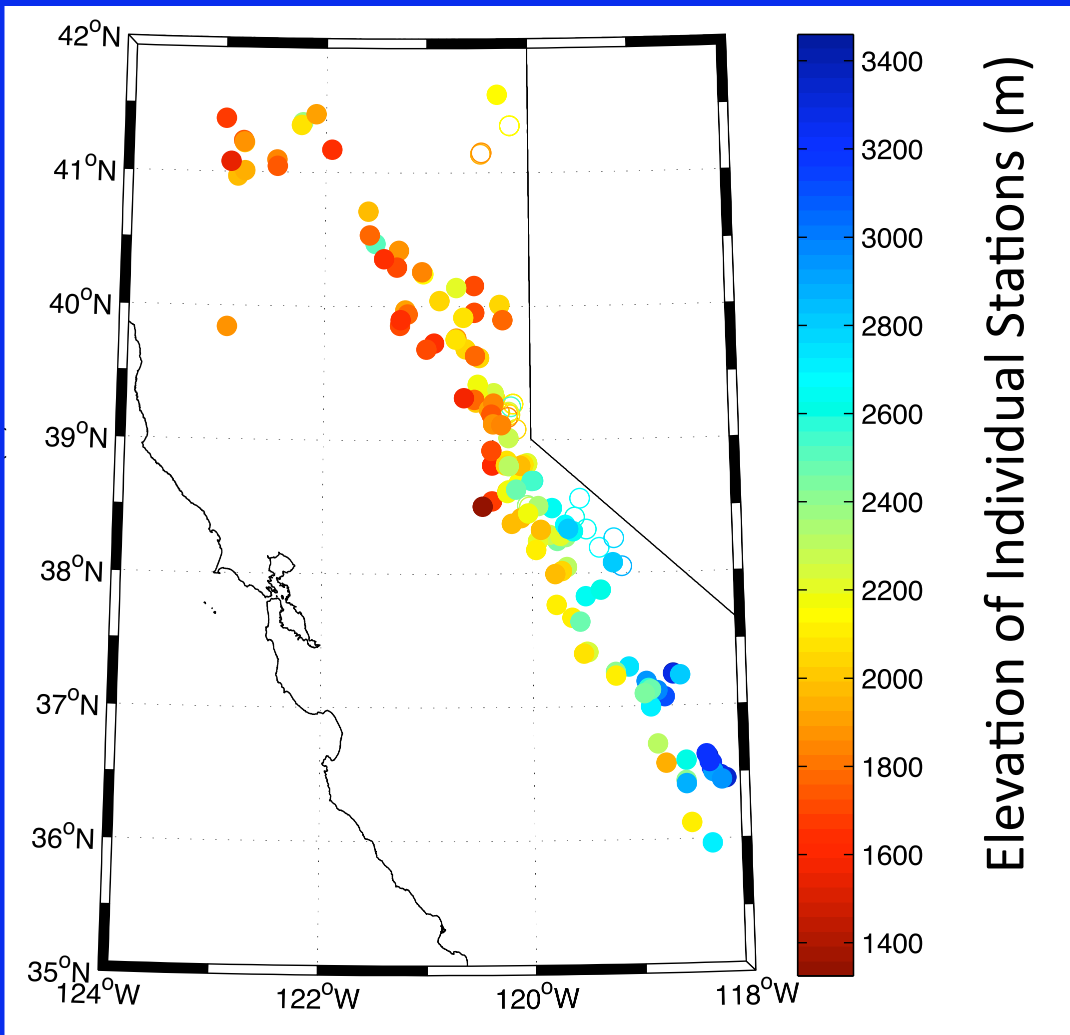
My Analysis of the Available SWE Observations Detection of Snowpack Climate Sensitivity

- Previous studies have focused on the robust April 1st SWE data set to detect changes in the snowpack in the American West, this metric is limited by its ambiguous relationship with accumulation and melt over individual snow seasons
- Moreover, previous monthly studies have also assumed measurement dates on the 1st of the month, which introduces error into trend analysis
- Given the overall temperature trend of warmer average March/April temperatures in the Sierras (0.1°C/decade from 1930 to 2003), how has the snowpack responded?
- Can a physical mechanism explain changes in snowpack evolution over a season and be quantified?

II. Methodology / Data Sets

Motivation: Available Historical Data

Monthly (~1st of Feb – ~1st of May) SWE Observations



- 154 stations with monthly Snow Water Equivalent ("SWE") measurements around the 1st of the month for a minimum of 15 years available from 1930-2008

Snow Mass Peak Date ("SCD")

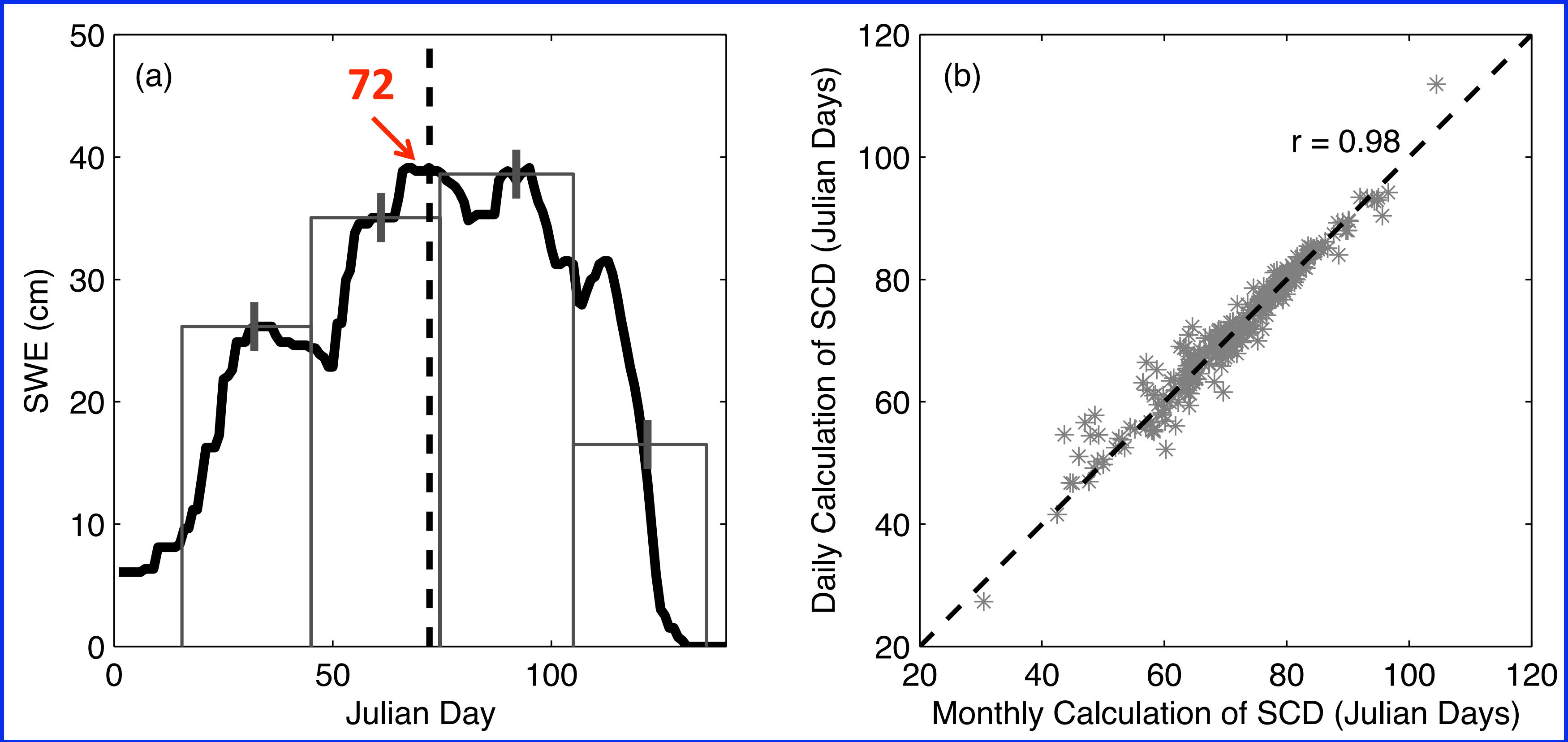
Calculation of Snowpack Metric

- The snow mass peak date for a particular year is given by the temporal centroid date of SWE values taken at 4 roughly-monthly measurement dates from mid-January to mid-May

$$\text{Snow Mass Peak Date} = \frac{\sum_{i=1}^{4} t_i SWE_i}{\sum_{i=1}^{4} SWE_i}$$

Snow Mass Peak Date ("SCD")

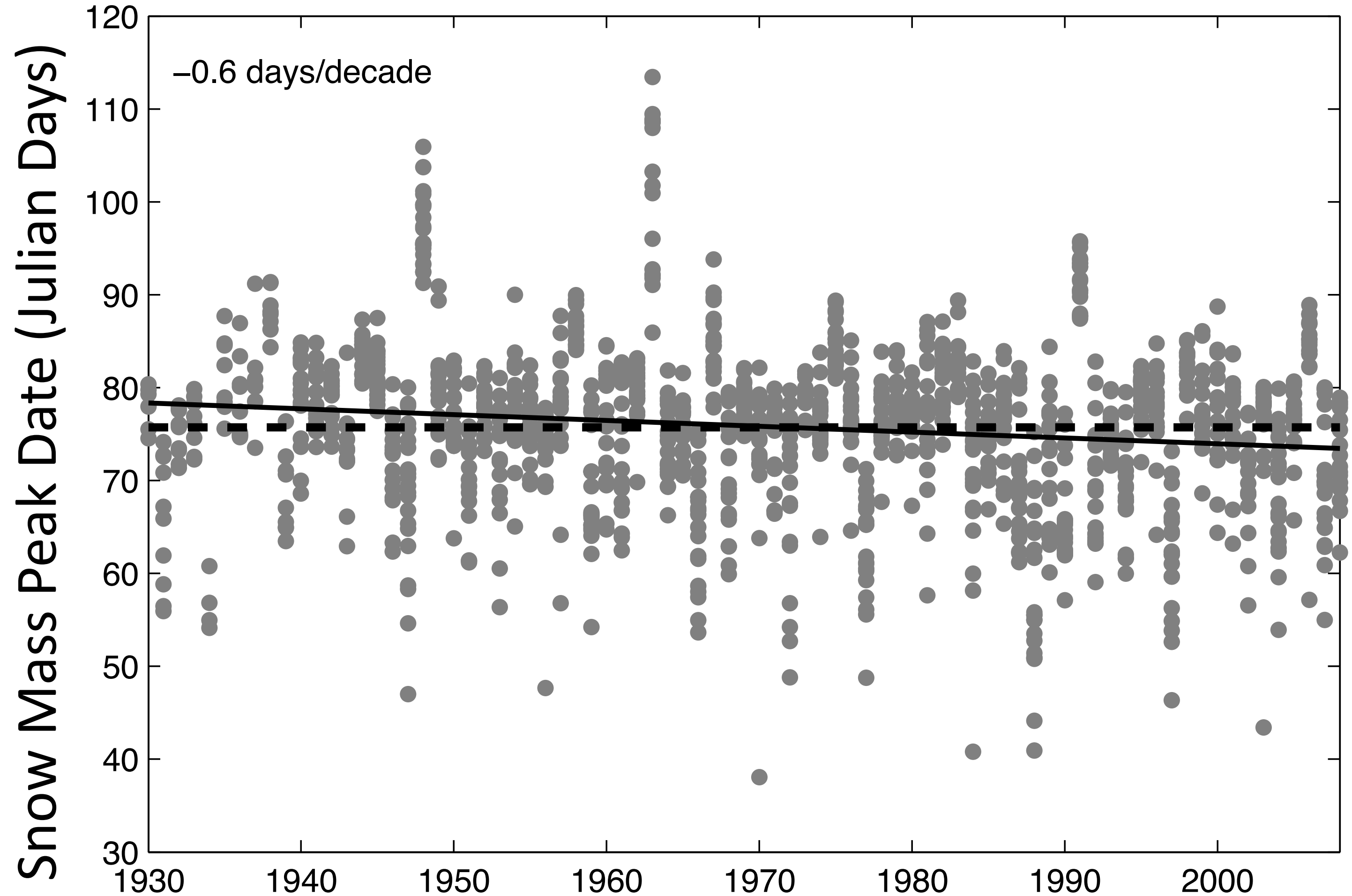
Calculations: '96 Adn Mtn Station and Daily vs. Monthly



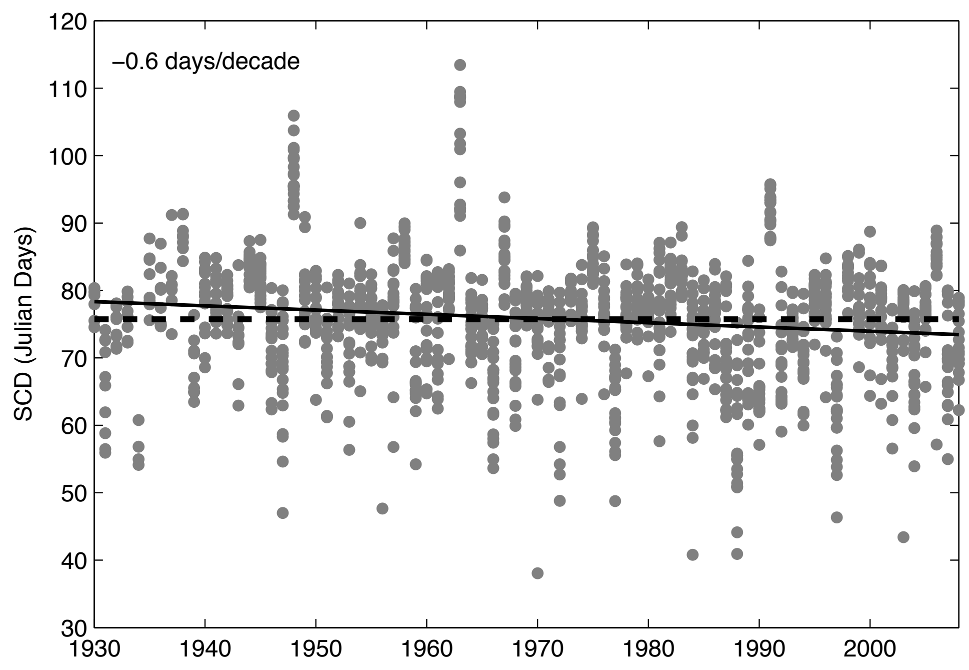
- Quantifies systematic changes in snow accumulation and melt timing
- Can determine such changes over the 79 year record despite the lack of daily data

III. Analysis

Trend in Snow Mass Peak Date
Slope Statistical Significance: $p<0.01$

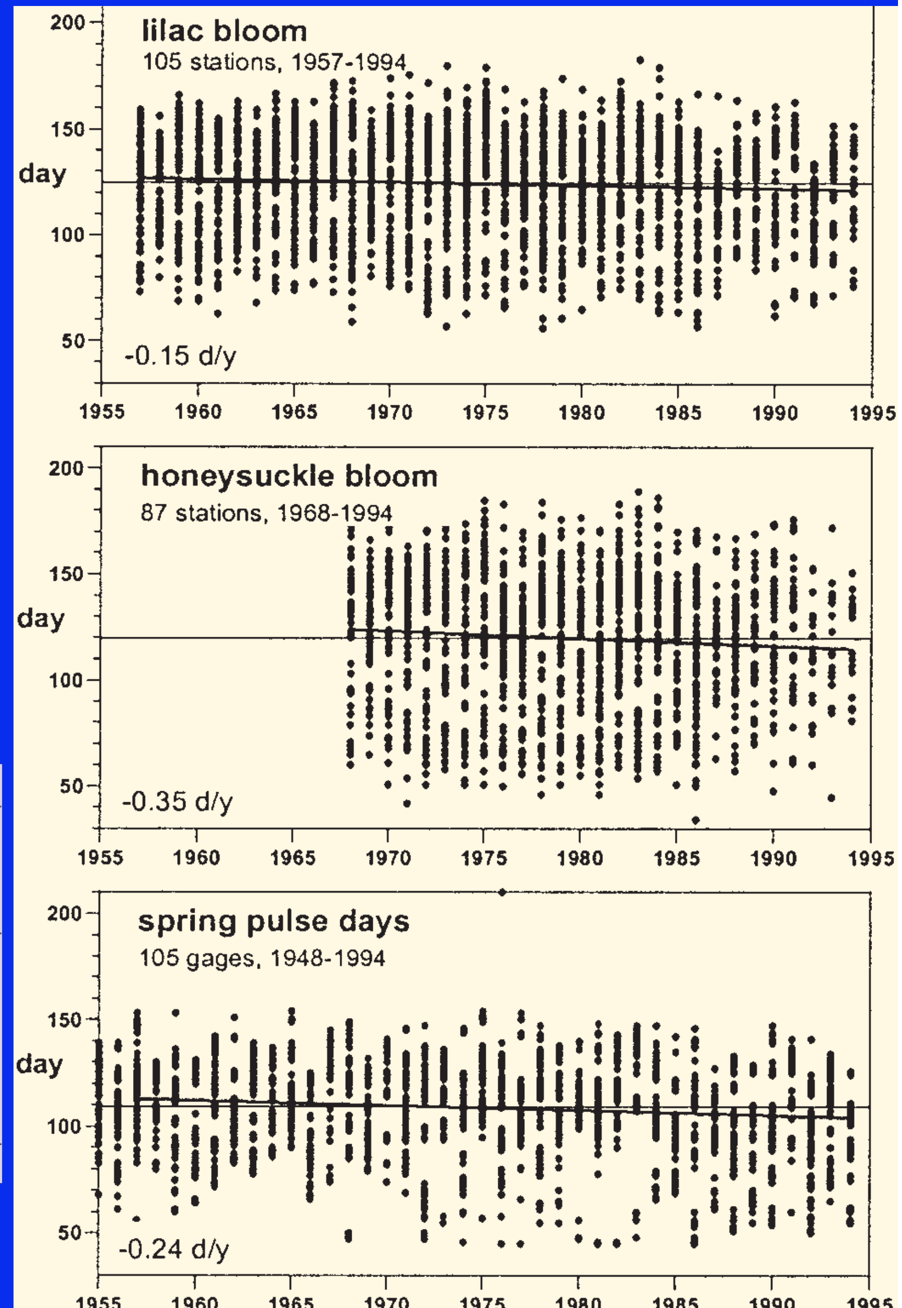


Sources: Similar to Cayan et al. 2001: "Changes in the Onset of Spring in the Western United States"



Days/Decade and Degrees/Year

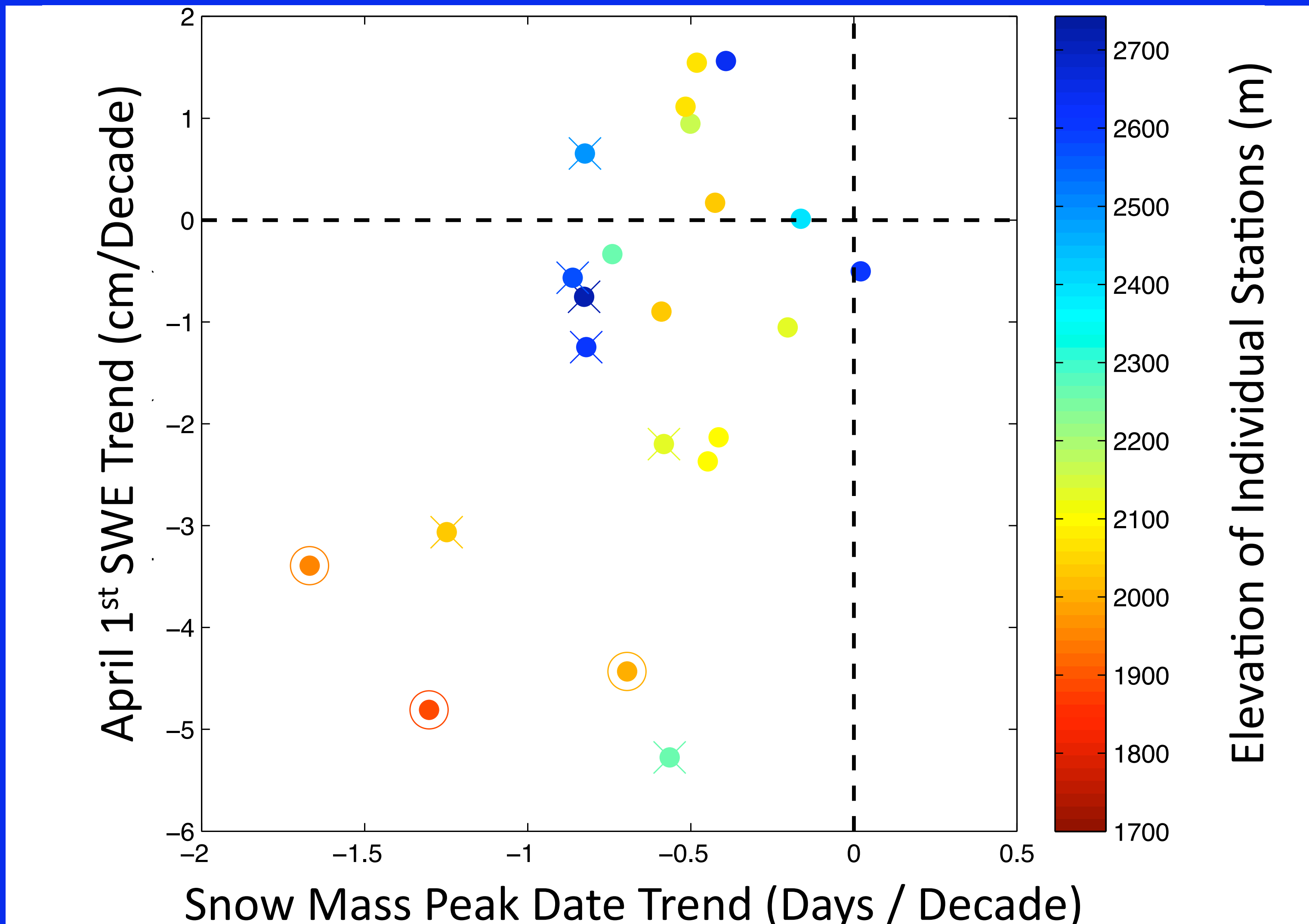
Case	1930	1940	1950	1960	1970
All Stations	-0.7	-0.8	-0.7	-0.7	-0.4
50% of Yrs	-1.0	-1.1	-0.7	-0.7	-0.7
75% of Yrs	**-0.6**	-0.9	-0.8	-1.0	-0.5
January Temp	0.3	0.3	0.5	0.5	0.7
February Temp	0.2	0.2	0.1	0.0	-0.1
March Temp	0.2	0.3	0.4	0.5	0.7
April Temp	0.0	0.1	0.1	0.3	0.5
May Temp	0.1	0.2	0.3	0.3	0.2
Averaged March & April Temp	0.1	0.2	0.3	0.4	0.6



Sources: Kapnick and Hall 2010; Cayan et al. 2001

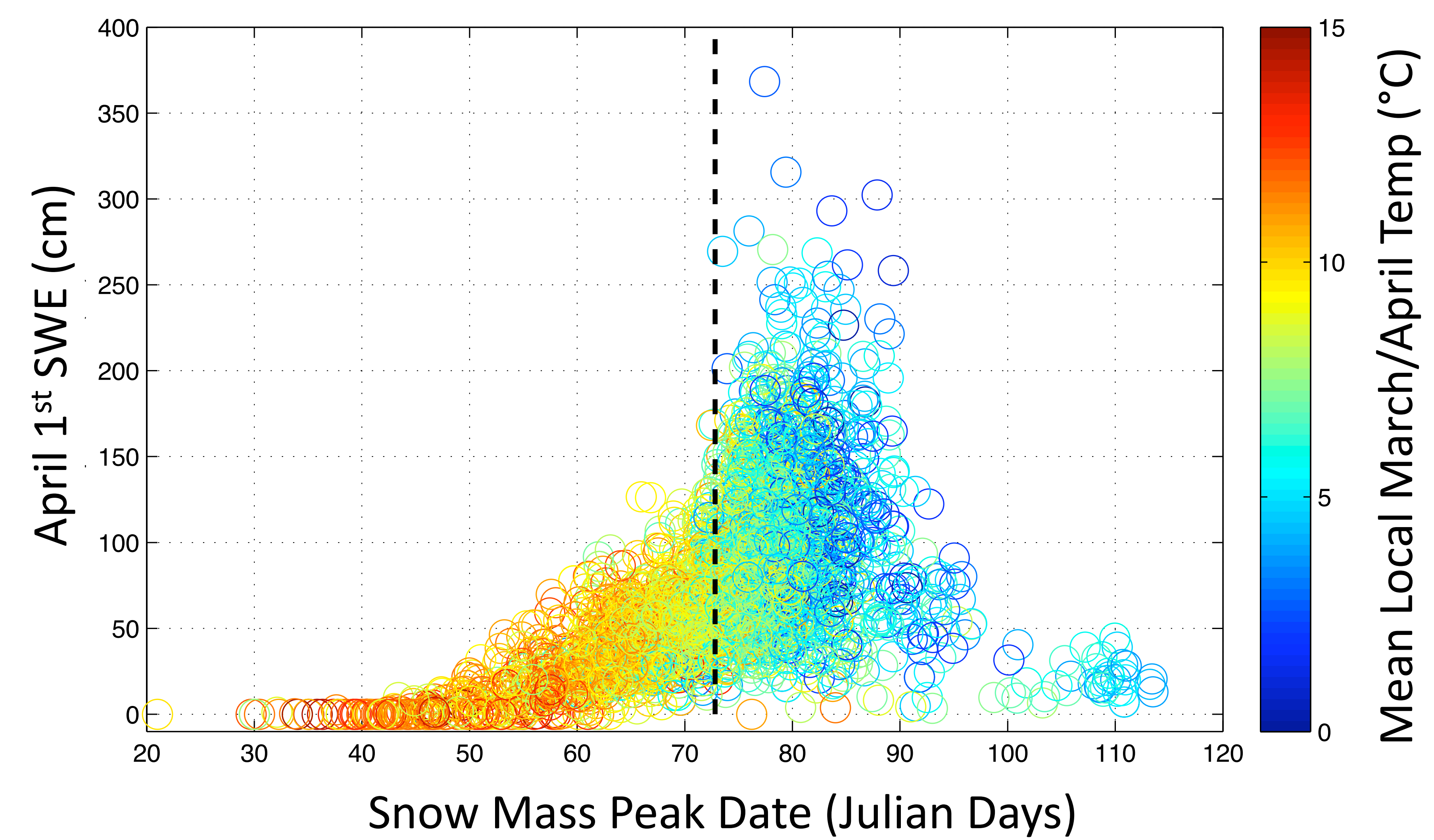
Trend in Snow Mass Peak Date

Individual Stations (Circled for significance p<0.05)



Snow Mass Peak Date vs. April 1st SWE

Colored by Mean March/April Temperature



Snow Mass Peak Date vs. April 1st SWE

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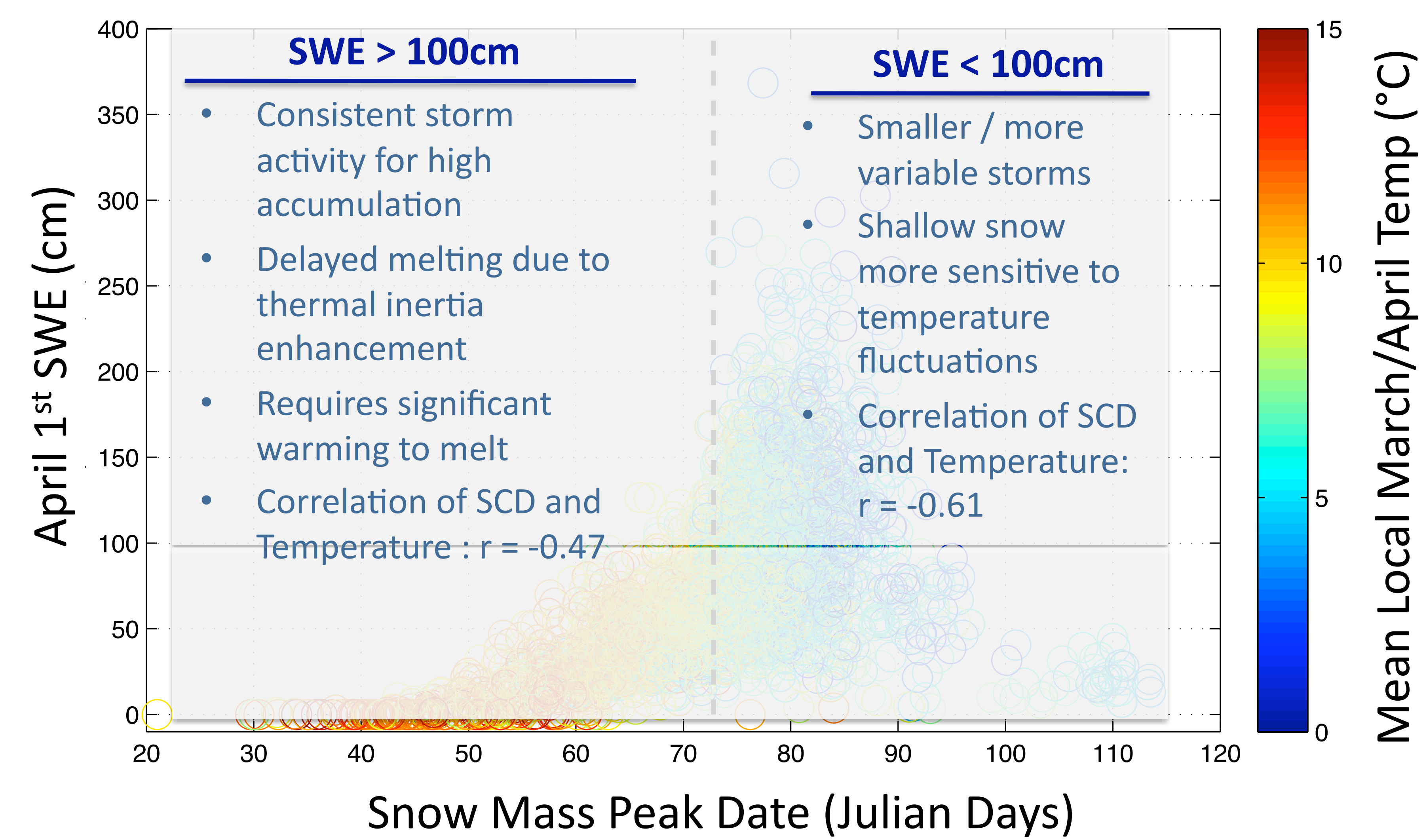
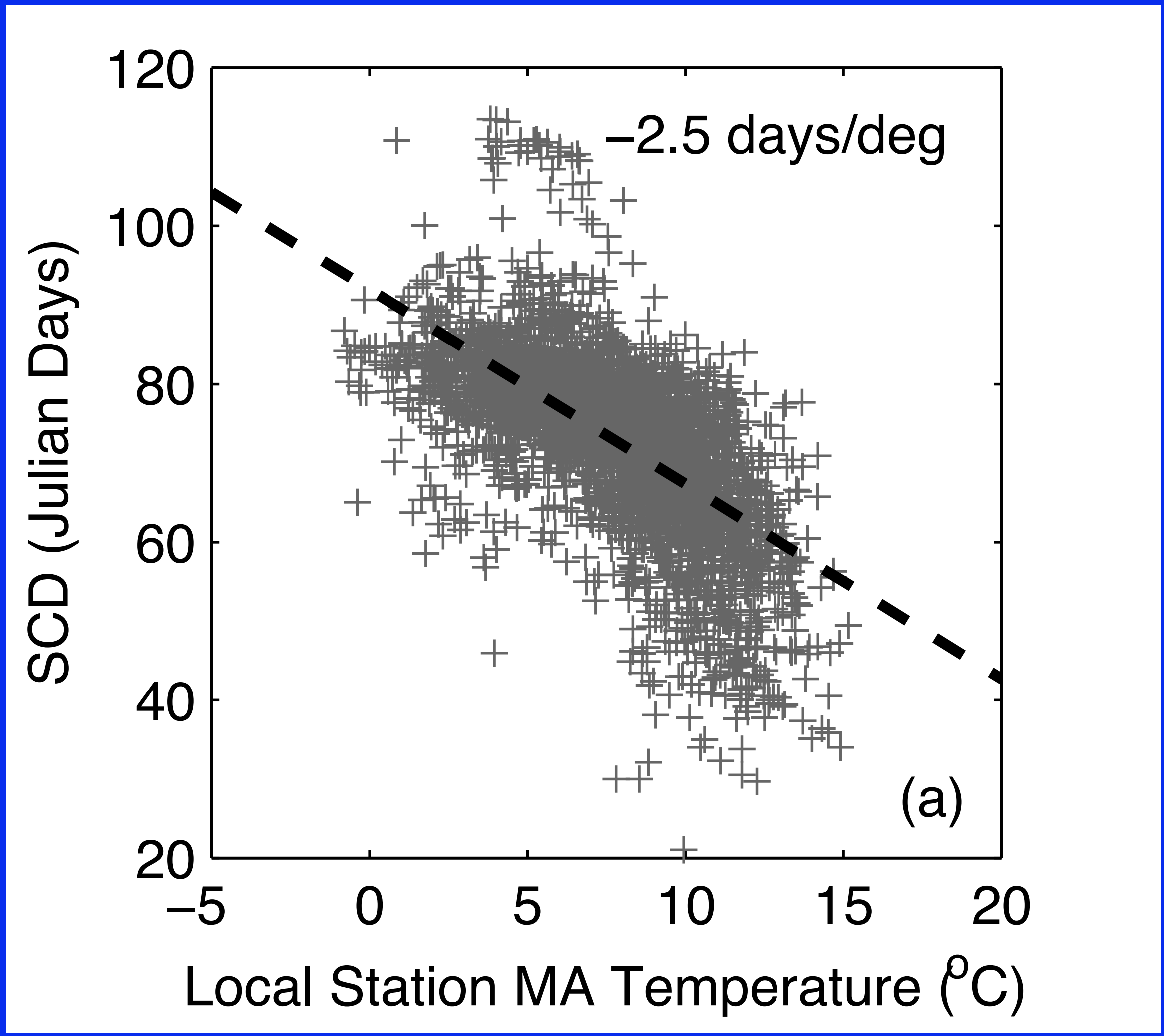


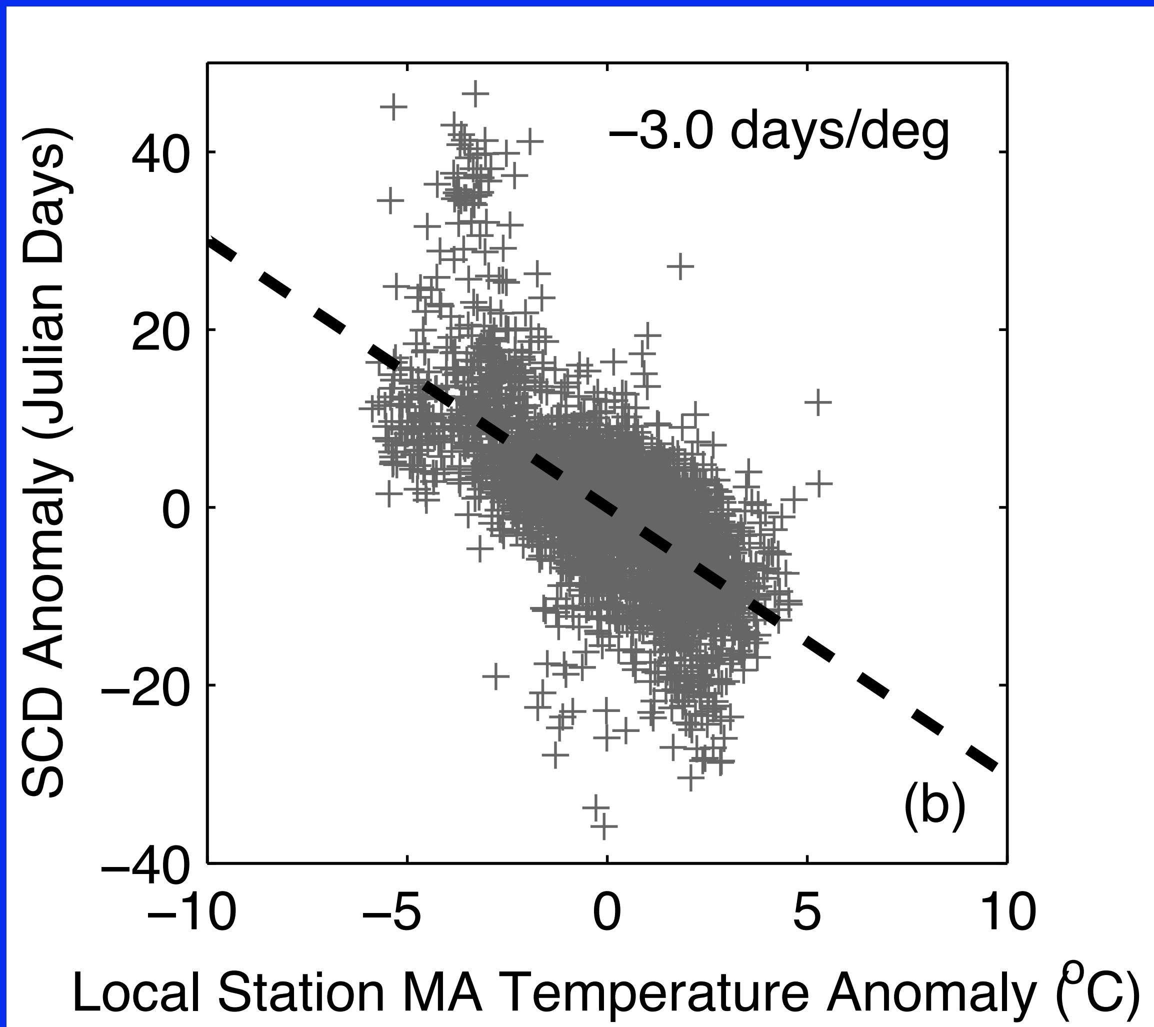
Snow Mass Peak Date vs. Temperature

Station Values: Slope=-2.5 days/°C, r=-0.62, p<0.01



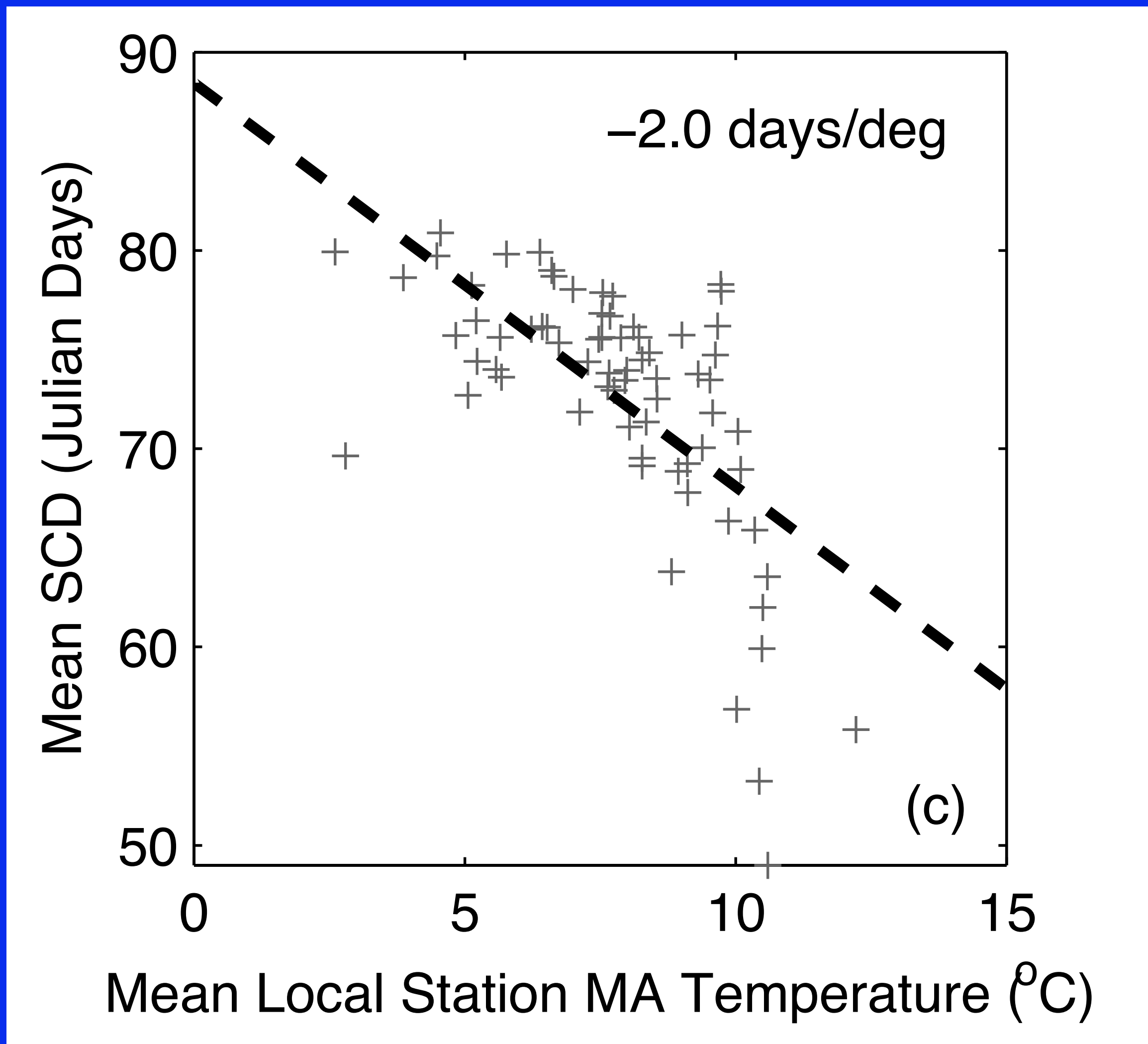
Snow Mass Peak Date vs. Temperature

Anomalies: Slope=-3.0 days/°C, r=-0.65, p<0.01



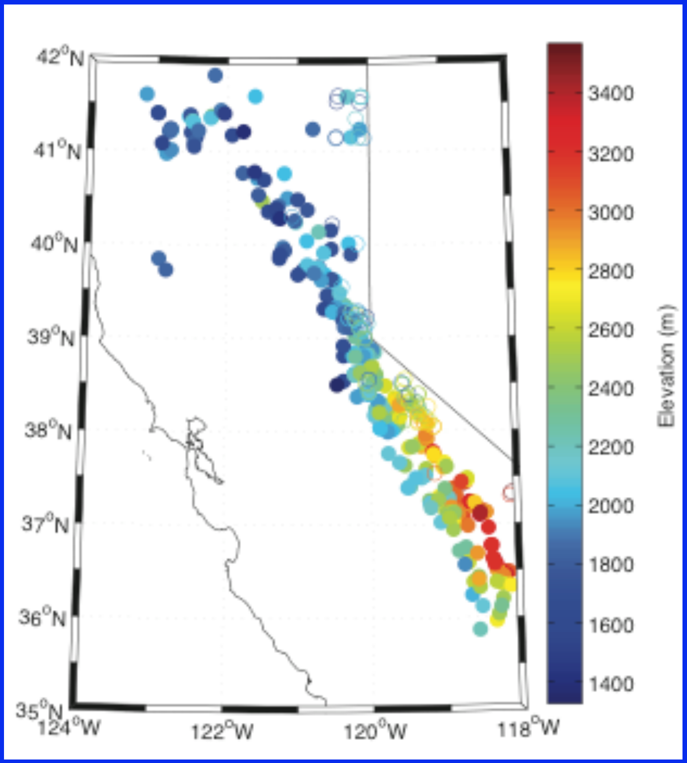
Snow Mass Peak Date vs. Temperature

Mean Values: Slope=-2.0 days/°C, r=-0.63, p<0.01



IV. Summary

a. Observations



Summary of Observational Findings

Climate Sensitivity of Snow Mass Peak Date

- Historical seasonal and inter-annual variability in the Sierra snowpack can be assessed using the snow mass peak date metric
- From 1930 to 2008, there has been a trend towards an earlier peak date of -0.6 days per decade, coinciding with a similar trend in temperature
- Early spring temperatures affect peak date almost certainly due to snowmelt processes
  - This relationship is particularly pronounced for low accumulation years
- The robustness in the sensitivity of snow mass peak date to averaged March and April temperature for all spatial and temporal scales included in the data set indicates the peak date trend can be attributed to the March and April warming trend

Implications of Findings from Observations

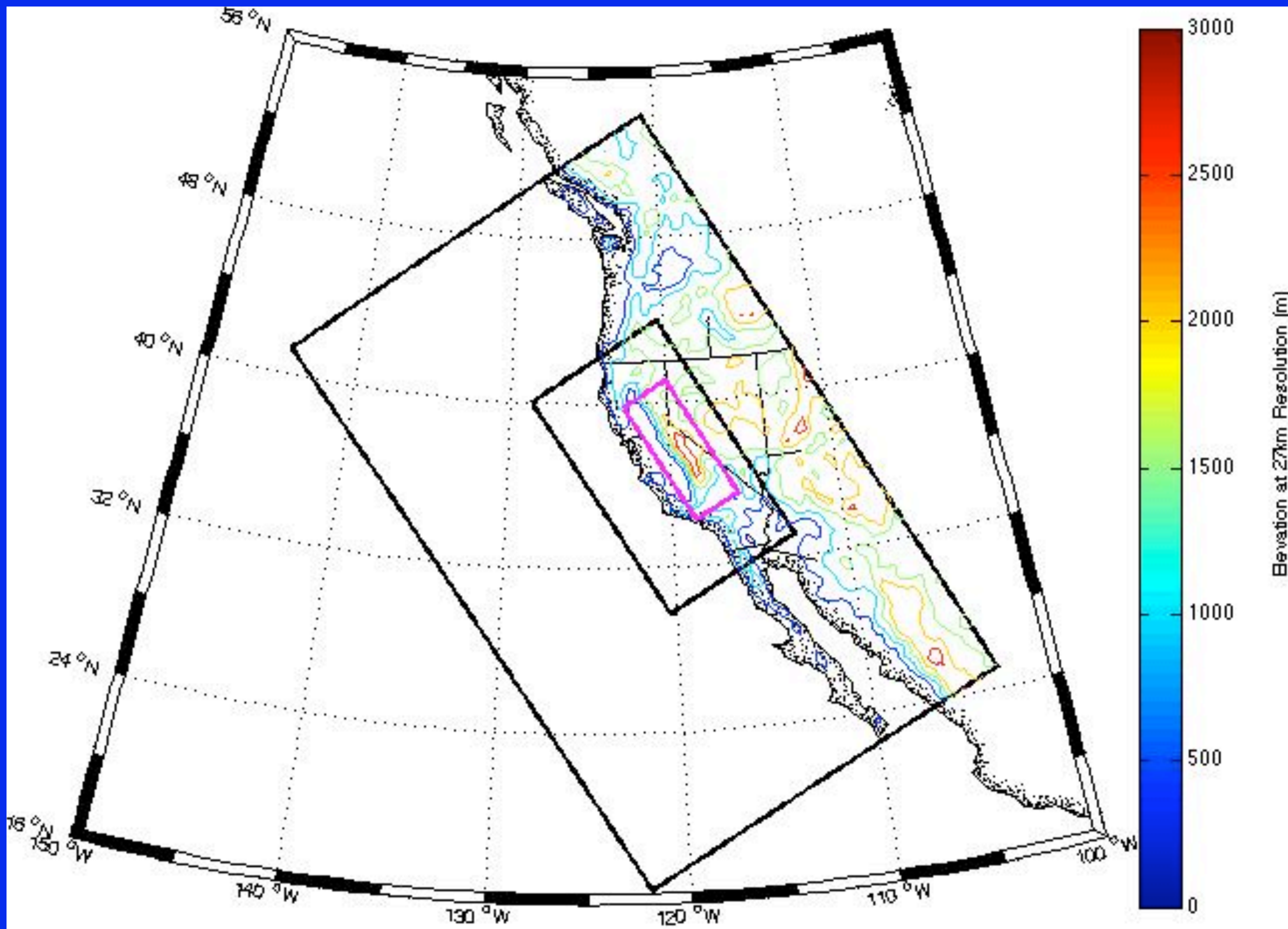
- Given projections of temperature increases in CA of 2°C to 7°C by the end of the century, this would imply an earlier snow mass peak date of 6 to 21 days
- A shift in the timing of resulting snowpack runoff would effect the reservoir maintenance of the California water supply from the Sierras

IV. Summary

b. Application of Observations to Modeling Studies

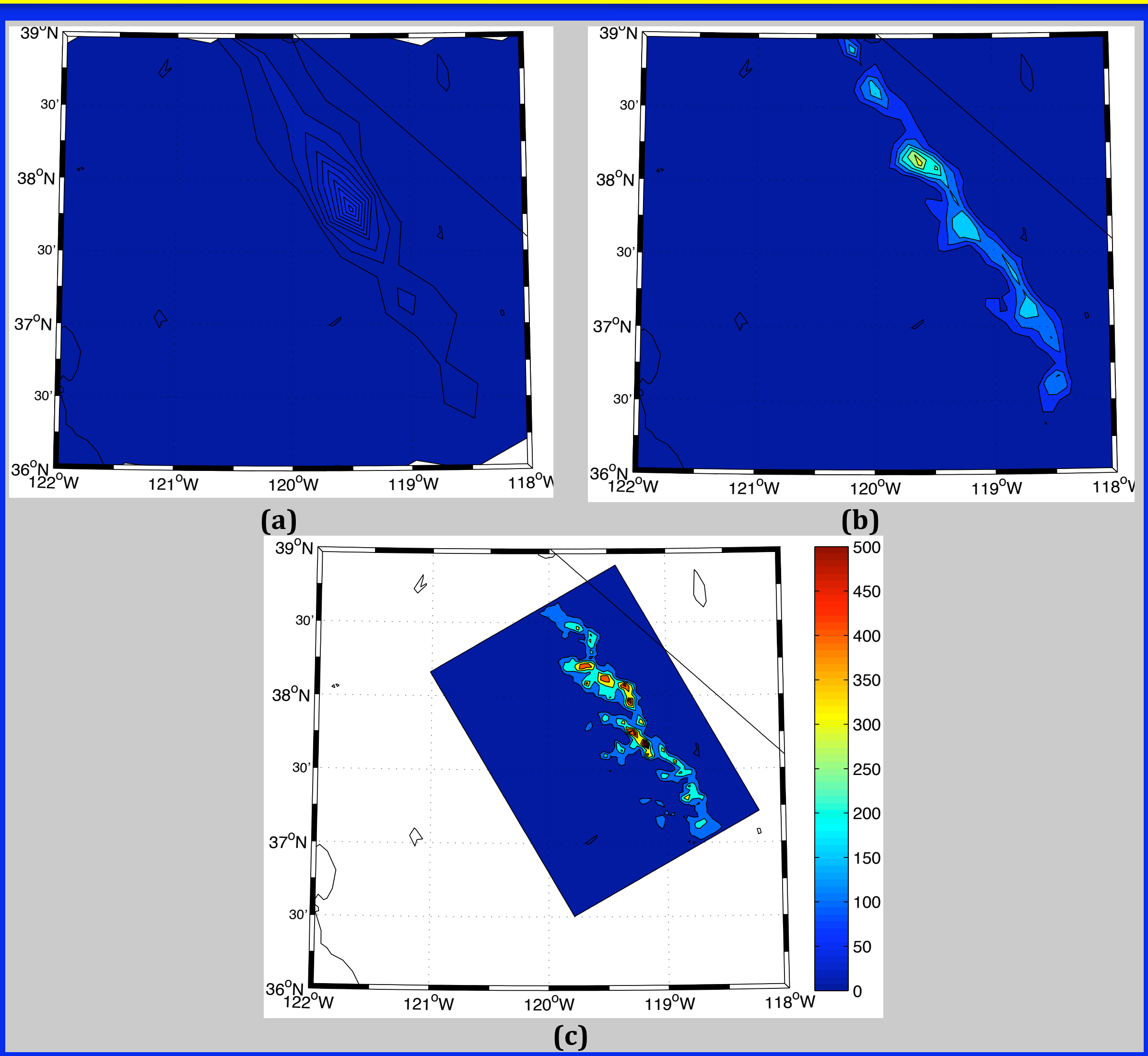
Goal: Quantify Errors Associated with WRF

Preliminary Analysis; WRF 3.1.1 Simulation: Nov. 2001-2002



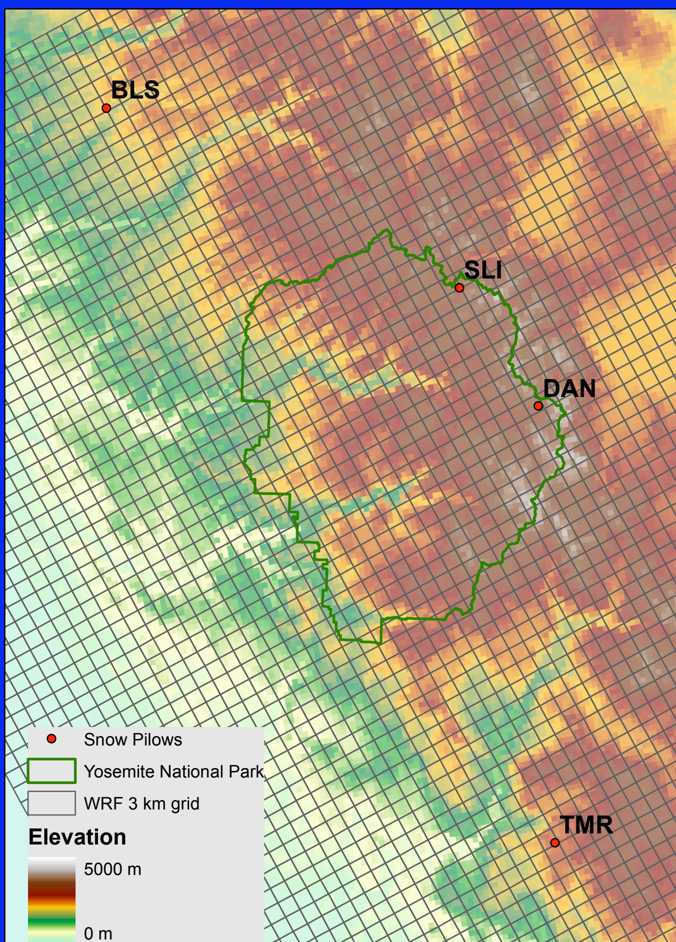
High Resolution Necessary over Yosemite

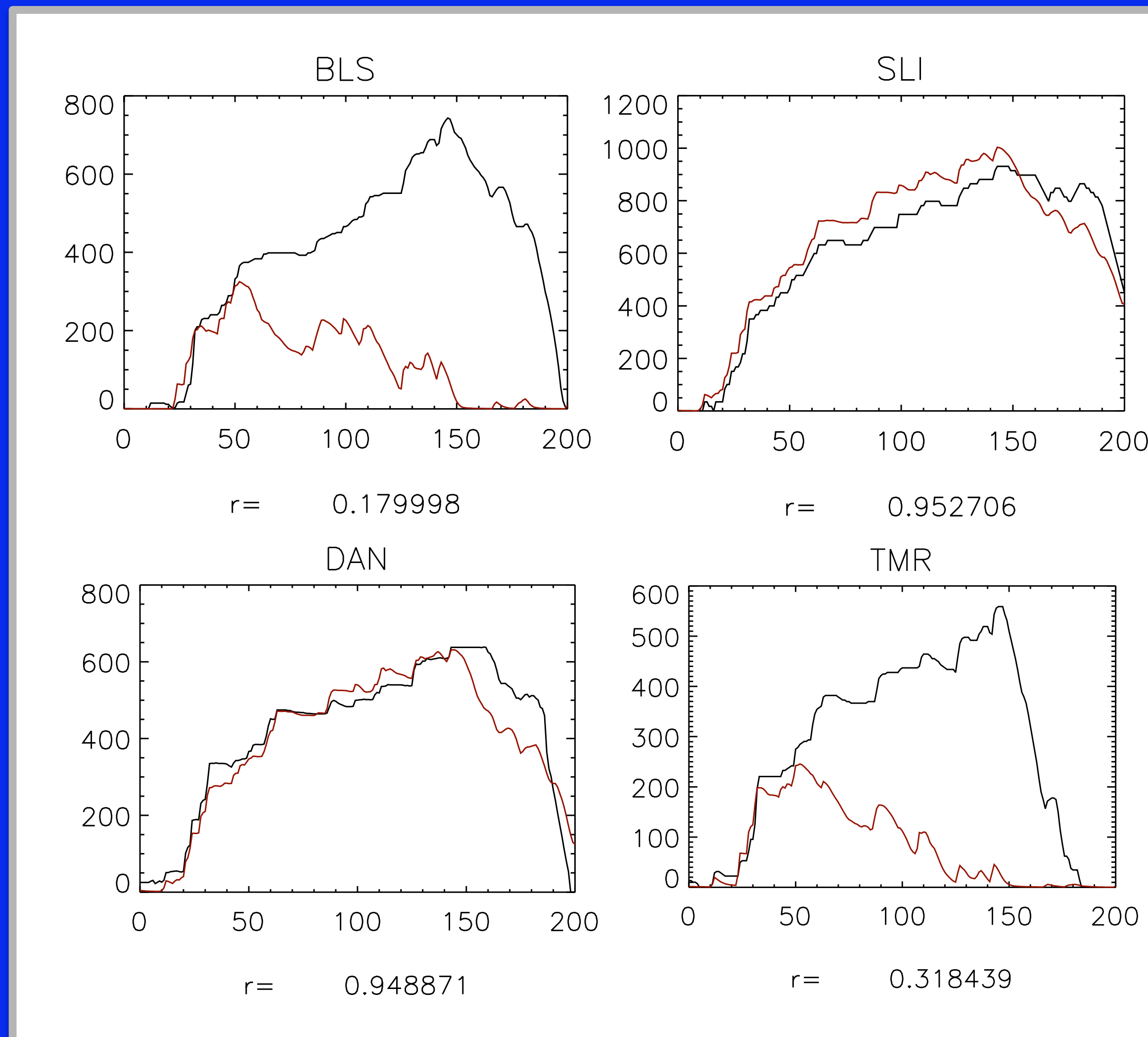
Average March, April, May SWE at (a) 27km (b) 9km (c) 3km



Some Stations Melting Too Early

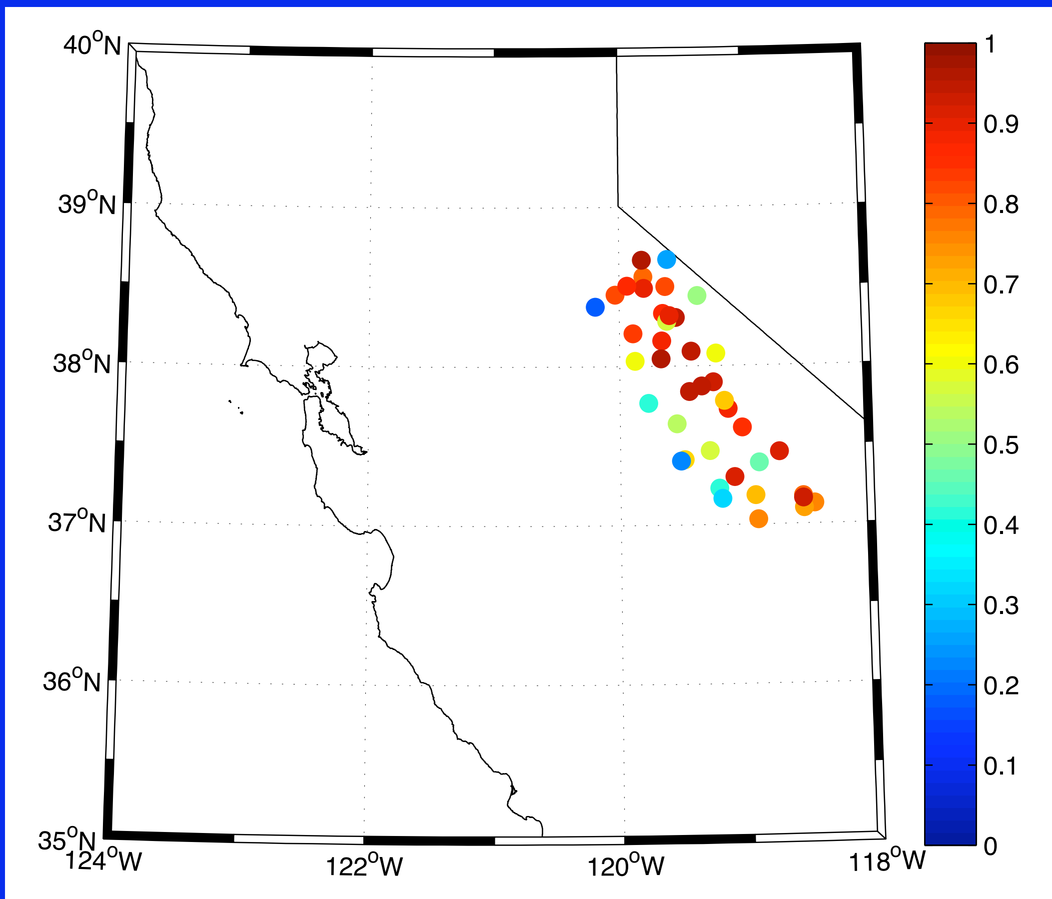
Note: Jan. 1 = 62; Feb. 1 = 93; Mar 1 = 121; Apr. 1 = 152; May 1 = 182





Sources: Pavlesky, Kapnick, and Hall 2010

Distribution of Station Correlation with Model Output



- Locations with good observation-model agreement occur along the ridge of the mountain range

Sources: Pavlesky, Kapnick, and Hall 2010

Summary of Modeling Work

Early Findings from WRF 3.1.1 Simulations

- High resolutions (on the order of 3km) are needed to produce reasonable snow cover and SWE magnitudes
- Preliminary comparisons to daily snow stations show good agreement at stations located along the Sierra Ridge; discrepancies at other stations could be due to:
  - Lack of accounting for diurnal cycles of melt and refreeze of the snowpack (once snow melts, it turns into runoff)
  - Errors associated with the resolution of observations (1m) versus model grid cells (3km)

VI. Acknowledgements

Acknowledgments

- This research has been supported by:
  - A NASA Earth and Space Sciences Graduate Student Fellowship
  - JPL
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- Collaborators on this work include:
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  - Tamlin Pavelsky, UNC-Chapel Hill